Galaxy Gas Halos
and
What They Can Tell Us About Galaxy Formation

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Why Gas Halos?

$\int$ Gas Accretion ↓ Star Formation ↓ Stellar Populations ↓ Dust dt

Gas Accretion ← Feedback ← Star Formation

$\frac{dM}{dt}$ Gas Accretion ↓↑ Feedback

Gas halos are a much simpler probe of gas physics.

They are sensitive to recent history ~ Gyr

It's all gas accretion!

There are four main things we are trying to understand with a theory of galaxy formation:

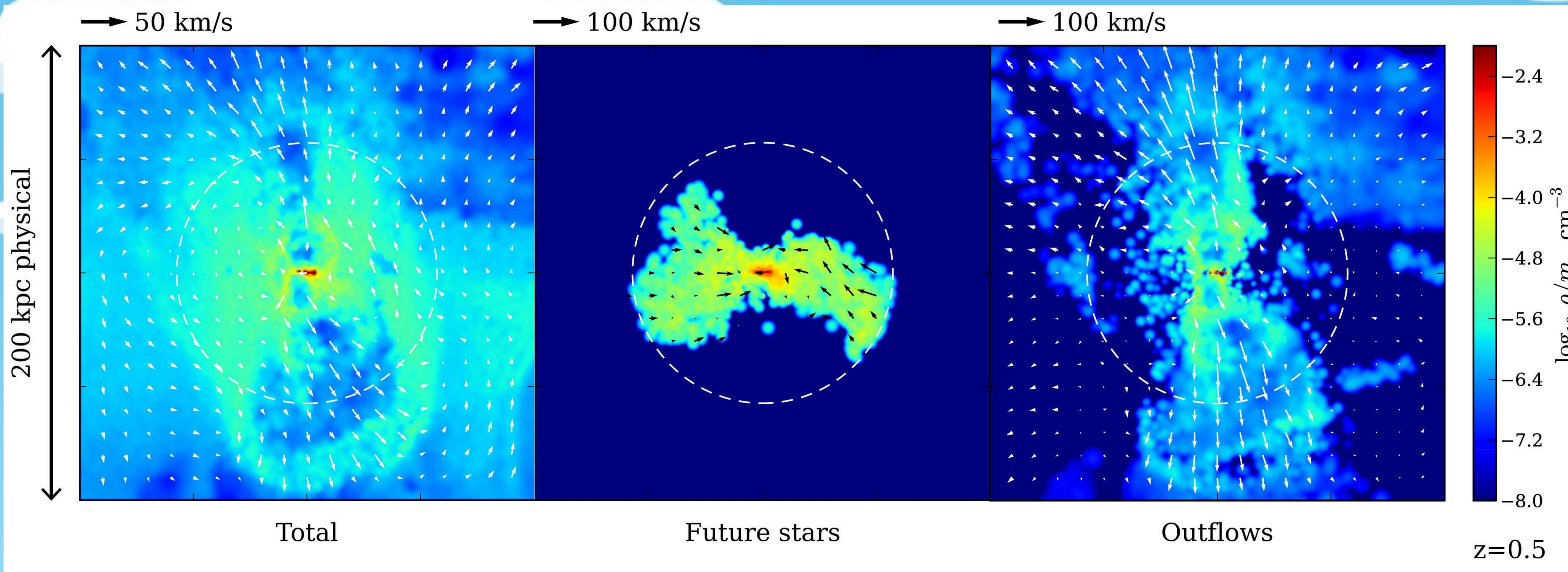
1. The masses of galaxies — gas accretion
2. The colors of galaxies — gas accretion
3. The sizes of galaxies — angular momentum
4. The morphologies of galaxies

Disk sizes are set by angular momentum conservation.

Fall and Efstathiou 1980

But the galaxy is only a small fraction of the available baryons. The key is which baryons are in the galaxy.

Maller and Dekel, 2002



Brook et al. 2011

As seen in recent simulations.

It's all gas accretion!

There are four main things we are trying to understand with a theory of galaxy formation:

1. The masses of galaxies	gas accretion
2. The colors of galaxies	gas accretion
3. The sizes of galaxies	gas accretion
4. The morphologies of galaxies	merger history

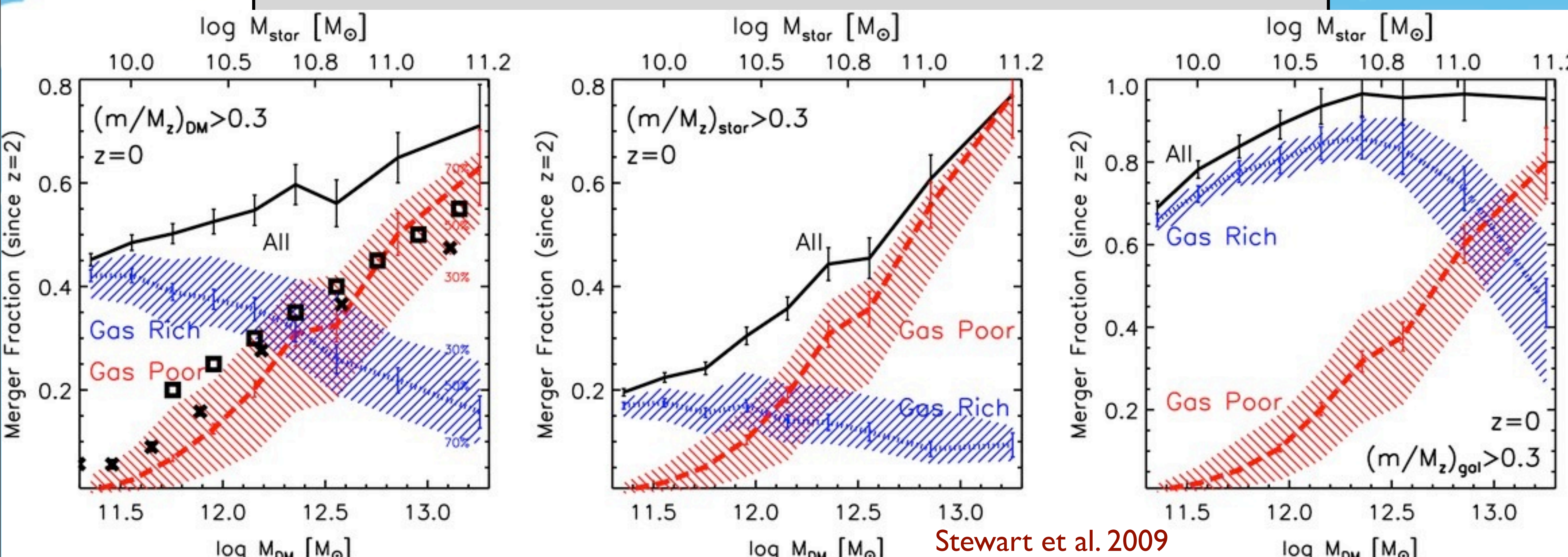
Galaxy morphology is related to galaxy mergers.

Toomre and Toomre 1972

However, dark matter halos almost never have major mergers.

Stewart, et al. 2009

In order to have major mergers, gas accretion must be less efficient in massive halos then in less massive ones.



Stewart et al. 2009

Maller 2006

m/M_{halo} $m/M_{stellar}$

It's all gas accretion!

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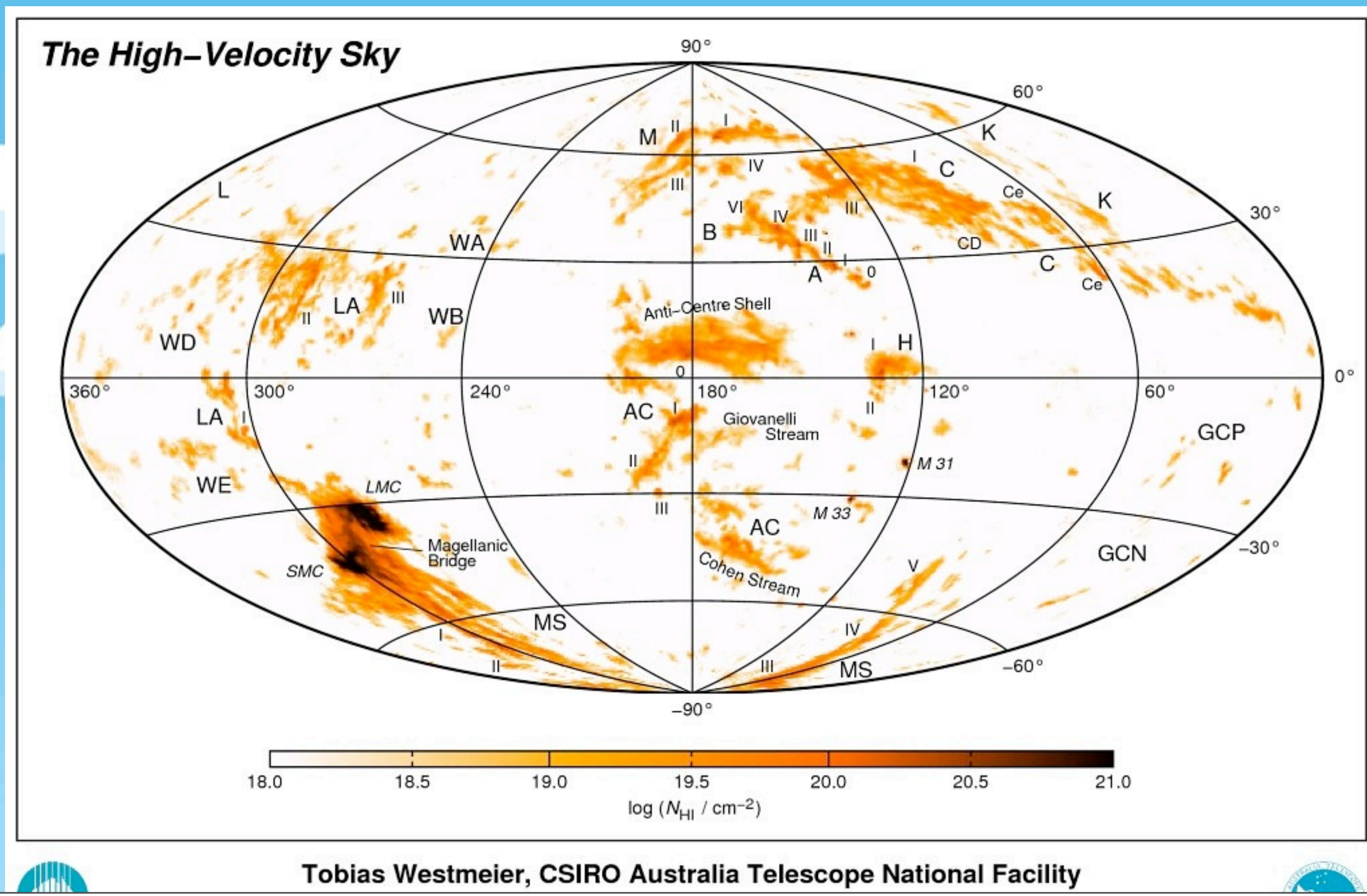
Identifying Structures

in

Milky Way Gas

High velocity gas has long been detected around the Milky Way and suggested as possible halo gas (Oort 1967).

In order to compare to models we would like to characterize this gas, traditionally this has been done as clouds and complexes.



Clouds have been defined as a contiguous region above a survey dependent flux threshold.

Clouds are resolution and sensitivity dependent. Single clouds are broken into smaller systems when higher resolution is used.

Complexes are cloud groupings that are done by visual inspection.

Clearly there are groupings in the clouds, but without an algorithm how can one determine if there are similar groupings in a model.

I got into this cause Maller & Bullock 2004, Kaufmann et al. 2009 suggests there should be lots of warm clouds around the Milky Way. Can we test this?

Radio Surveys

We have applied this algorithm on two radio surveys:

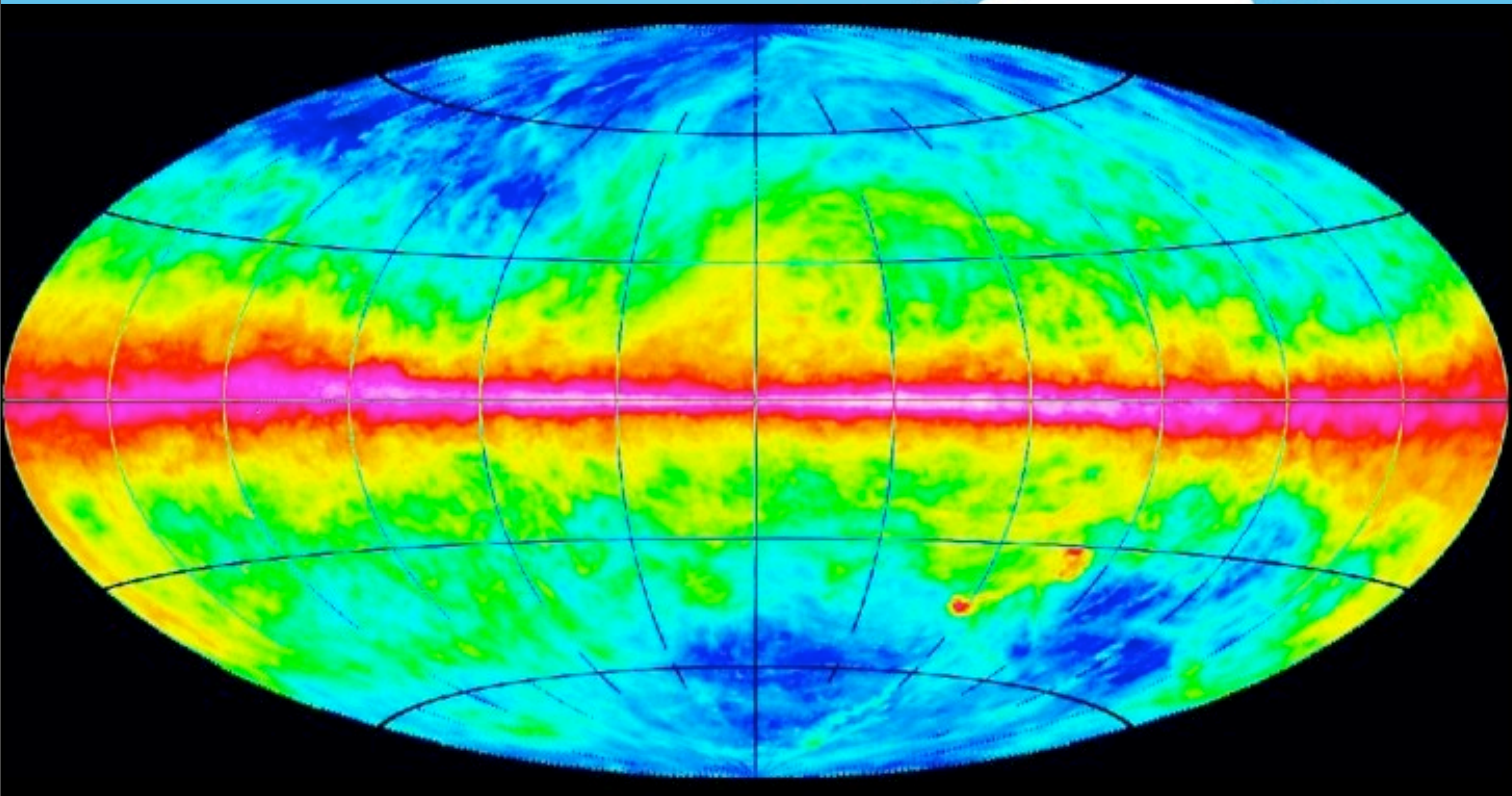
The Lieden/Argintina/Bonn (LAB) survey which covers the entire sky with a angular resolution of 0.6 degrees and velocity resolution of 1.3 km/s.

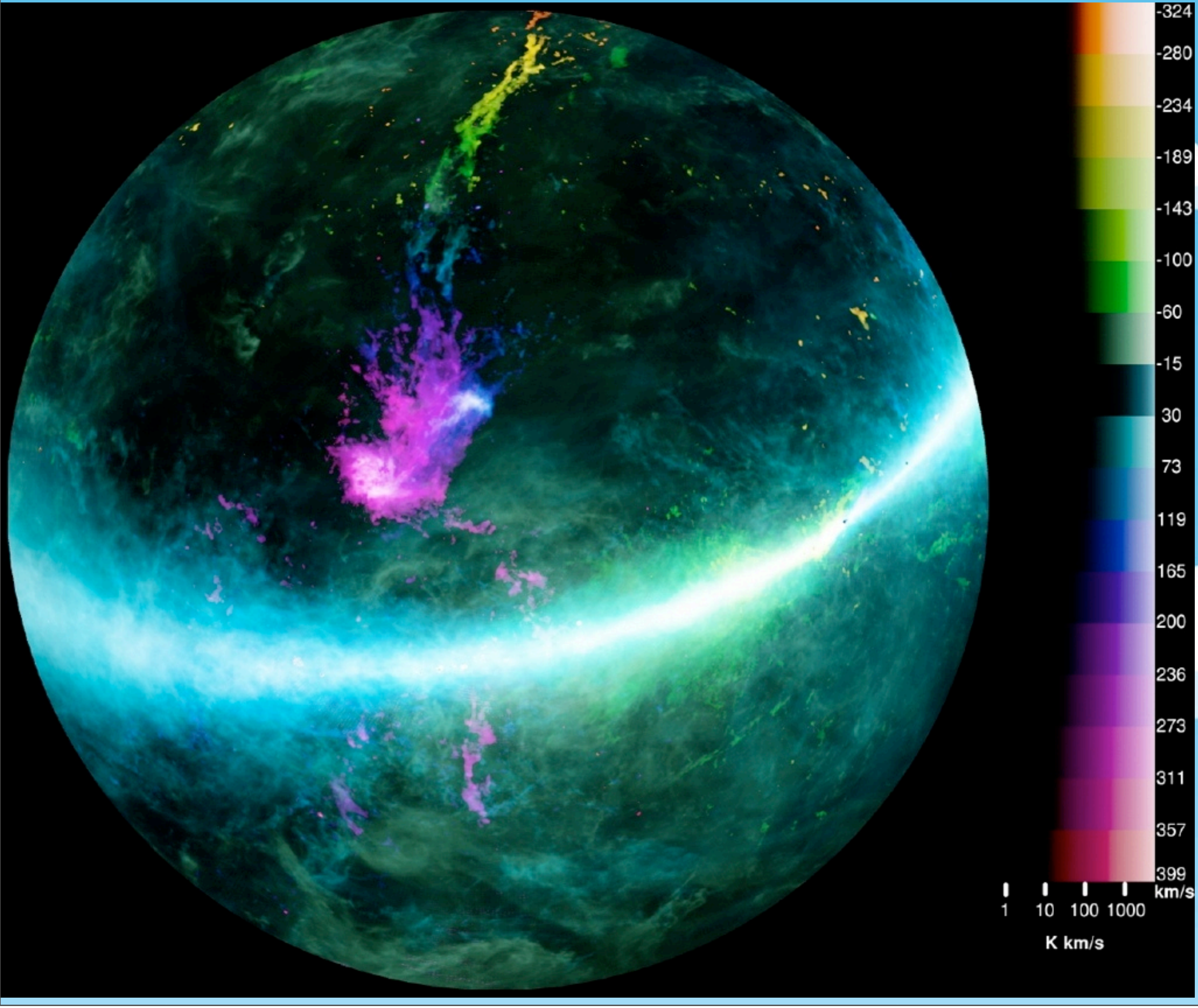
Kalberla et al, 2005

The Galaxy All Sky Survey (GASS) which covers the southern sky with 16 arcmin resolution and 0.82 km/s velocity resolution.

McClure-Griffiths et al, 2009

LAB




-324
-280
-234
-189
-143
-100
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30
73
119
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km/s
1
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EnLink

In order to improve upon this situation we have used EnLink, a sophisticated algorithm for finding structures in arbitrary data sets.

Sharma & Johnston 2009

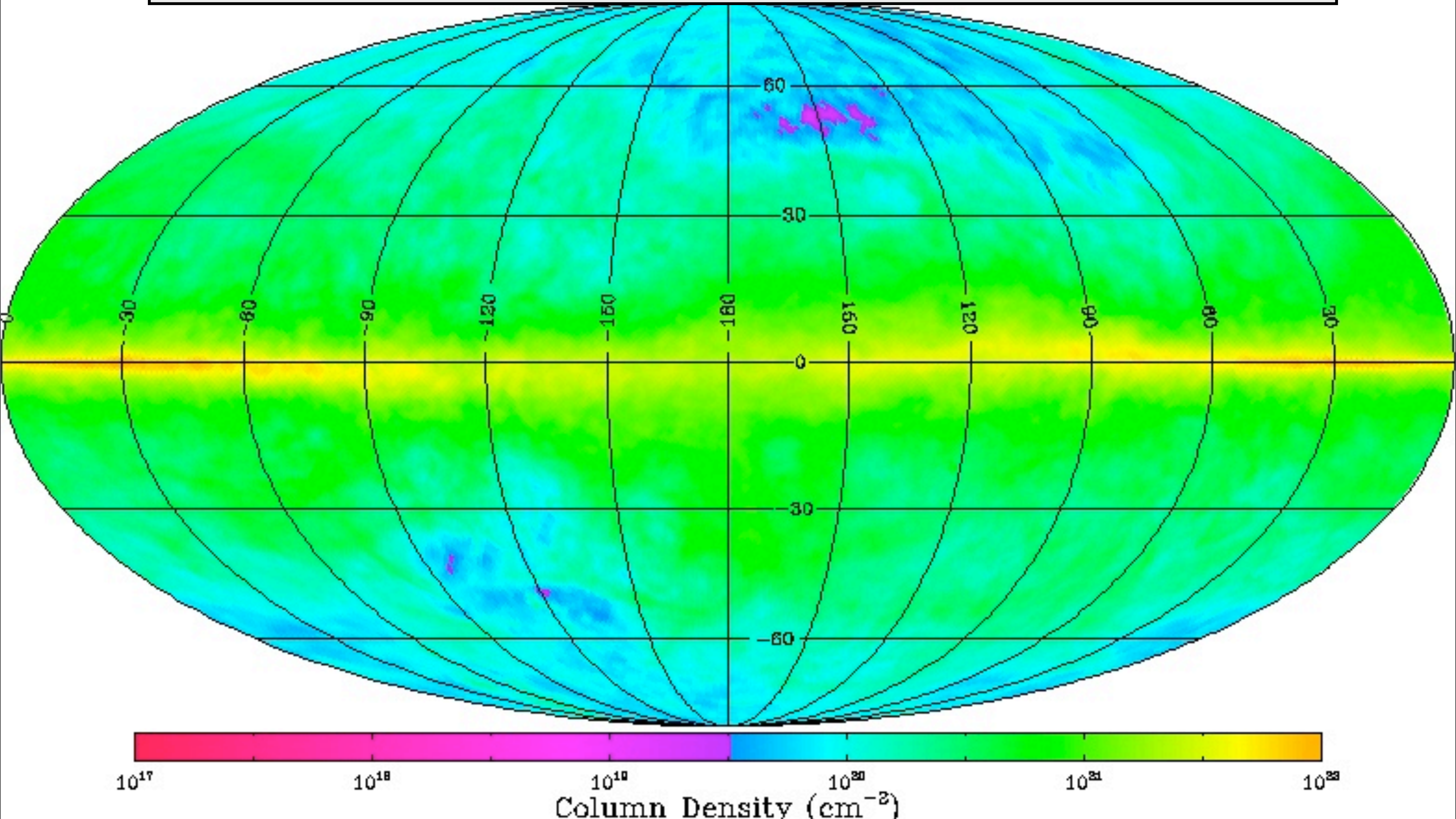
EnLink works in the following way:

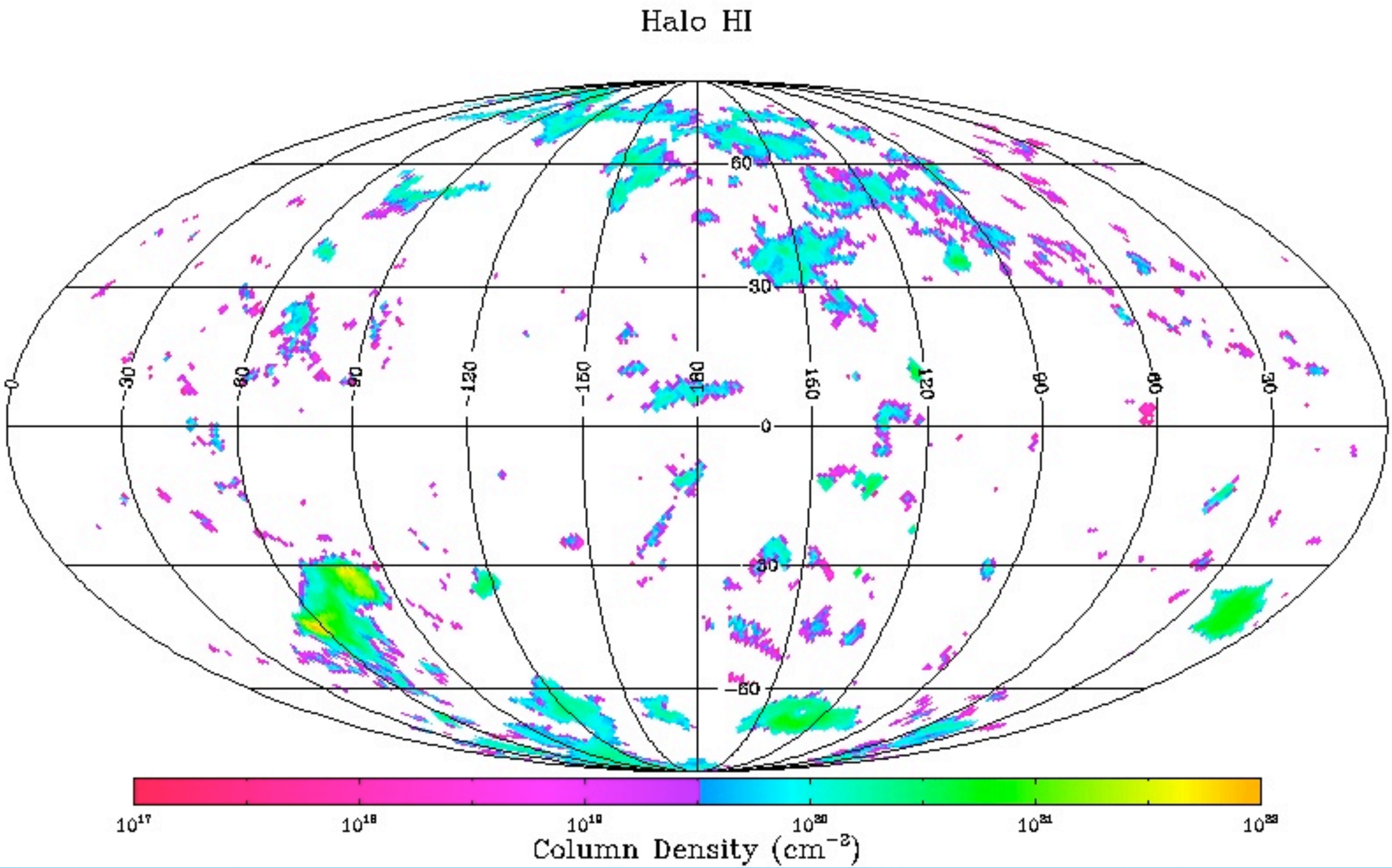
1. No preset definition of a metric.
2. Determines metric locally by maximizing information.
3. Builds clusters of points starting with locally densest point.
4. Attaches subclusters hierarchically with as many levels as needed.

similar to Behroozi, et al.'s Rockstar, ask him if you have questions.

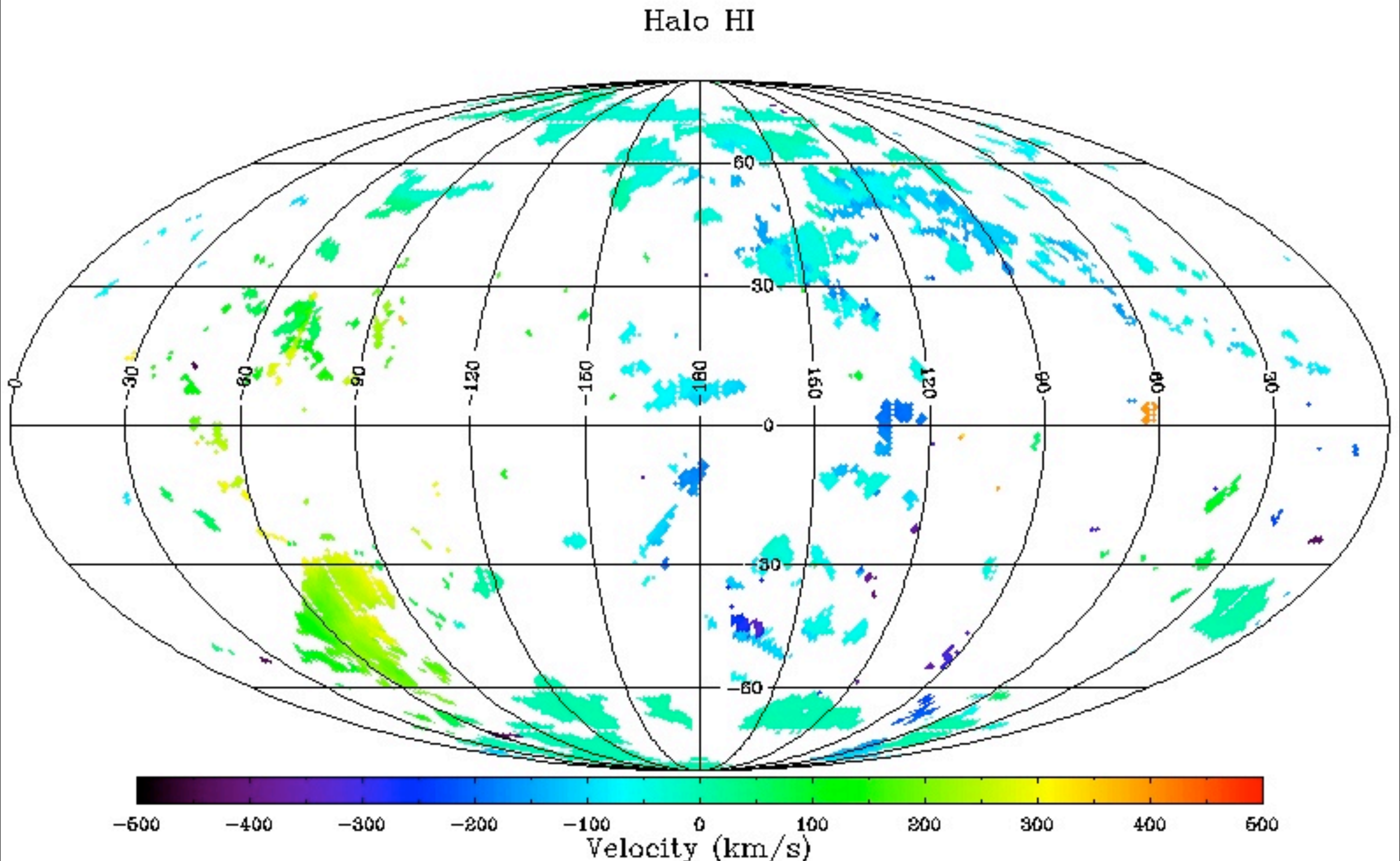
- We apply EnLink to these two data sets identifying structures in the phase space of angular position and velocity.
- We make no arbitrary velocity cut on the data. Structures are identified by being a locally dense region of the data space.
- In practice this allows us to recover the high velocity gas around the Milky Way.

We can separate the Milky Way as the largest group, containing 97% of the cells.

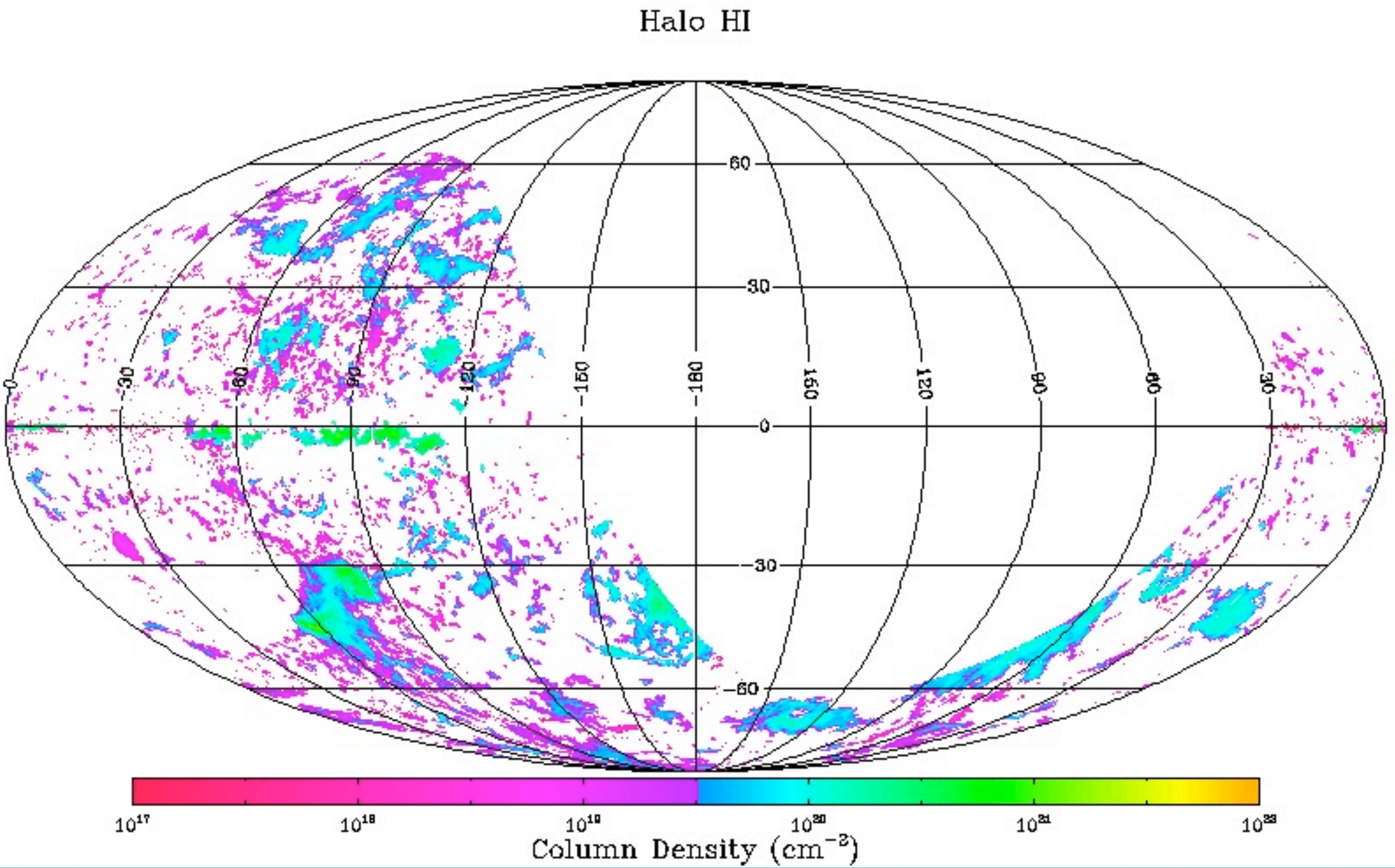




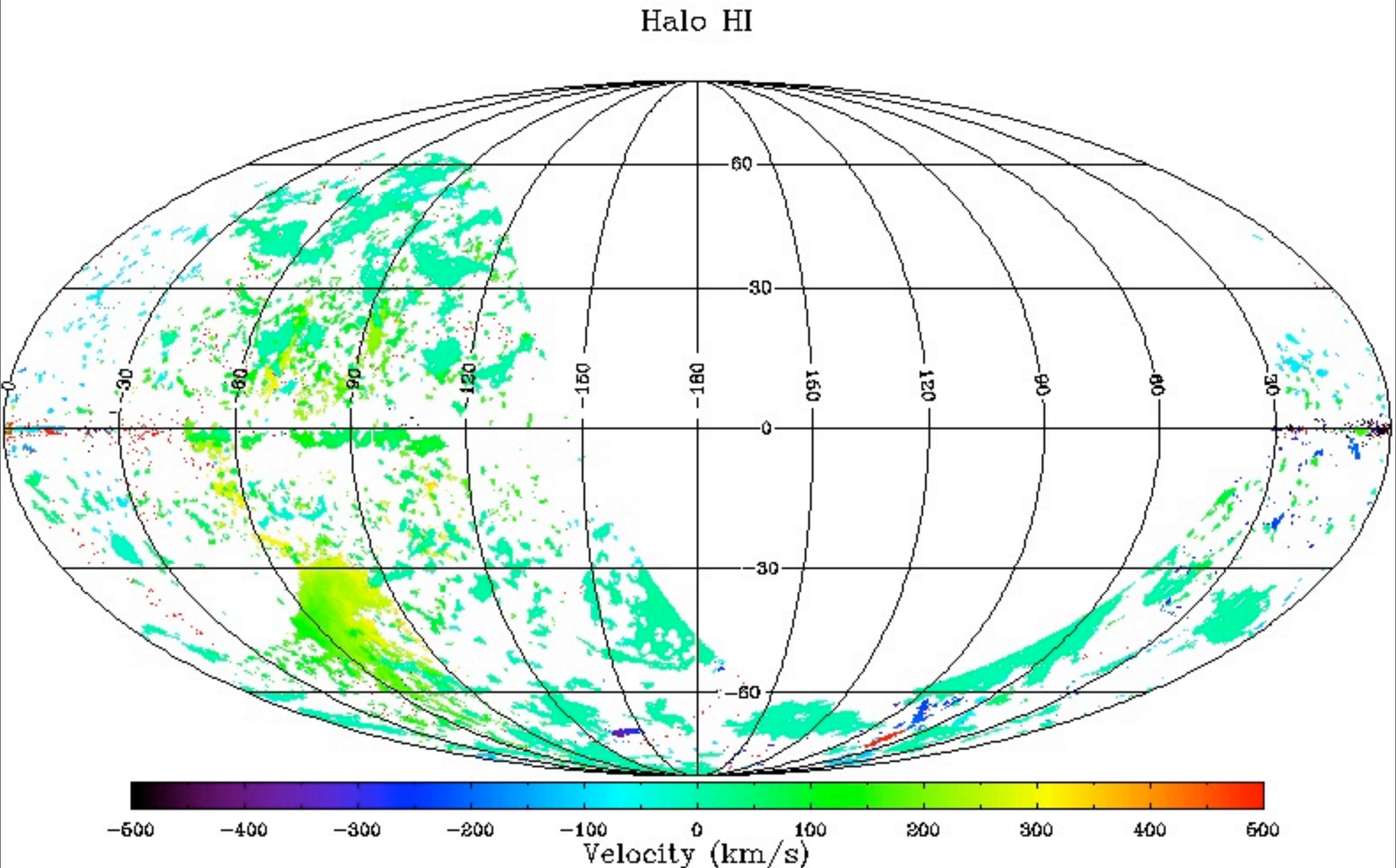
From other groups, without using a velocity cut.



Of course most of this is still at high velocity.



High velocity gas in GASS.

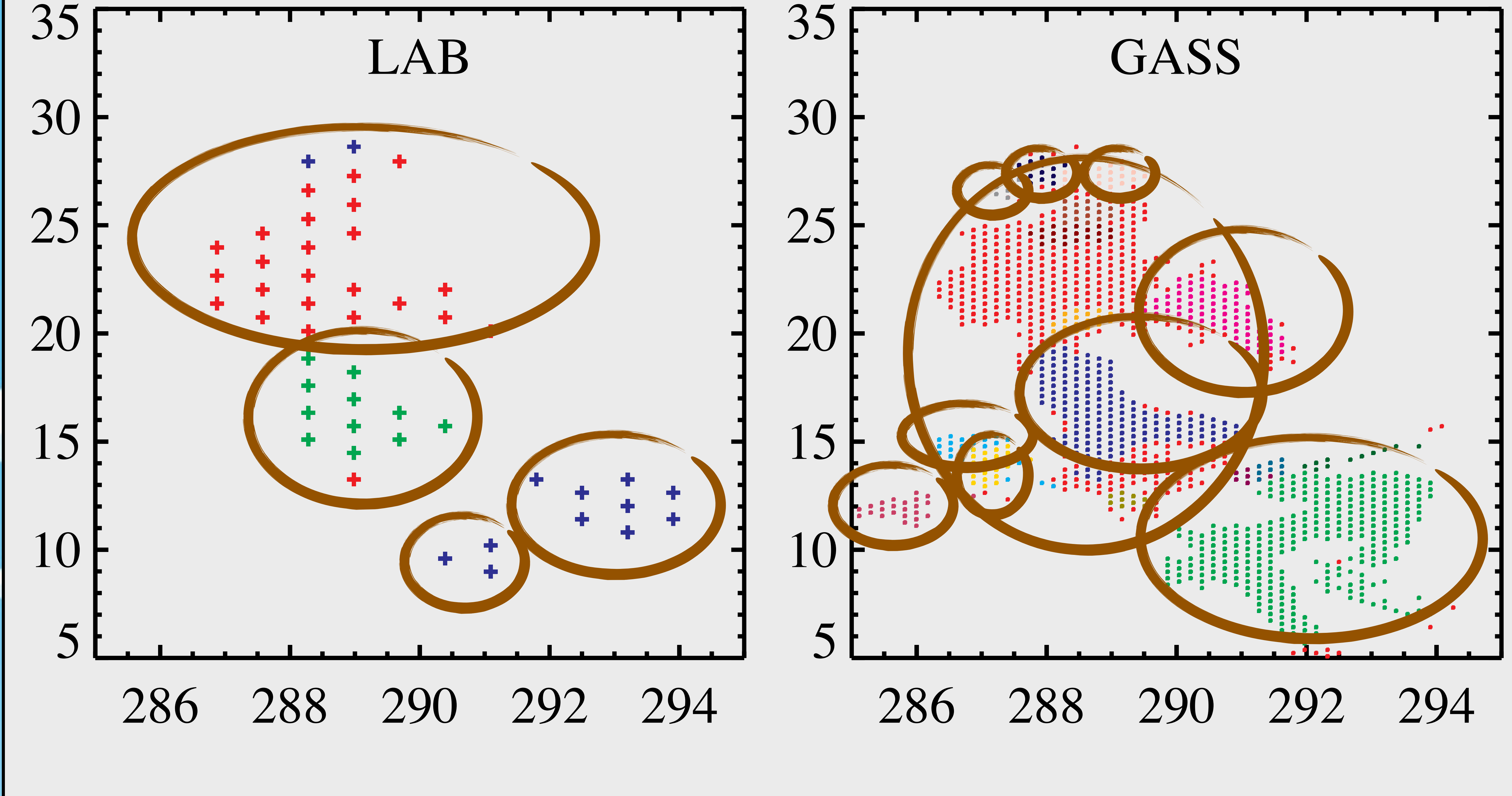


High velocity gas in GASS.

- EnLink is a hierarchal structure finder so it identifies a group, and then subgroups and then sub-subgroups, etc.

- The lowest level of structure will depend on resolution, but hopefully the highest level of structure will be resolution independent.

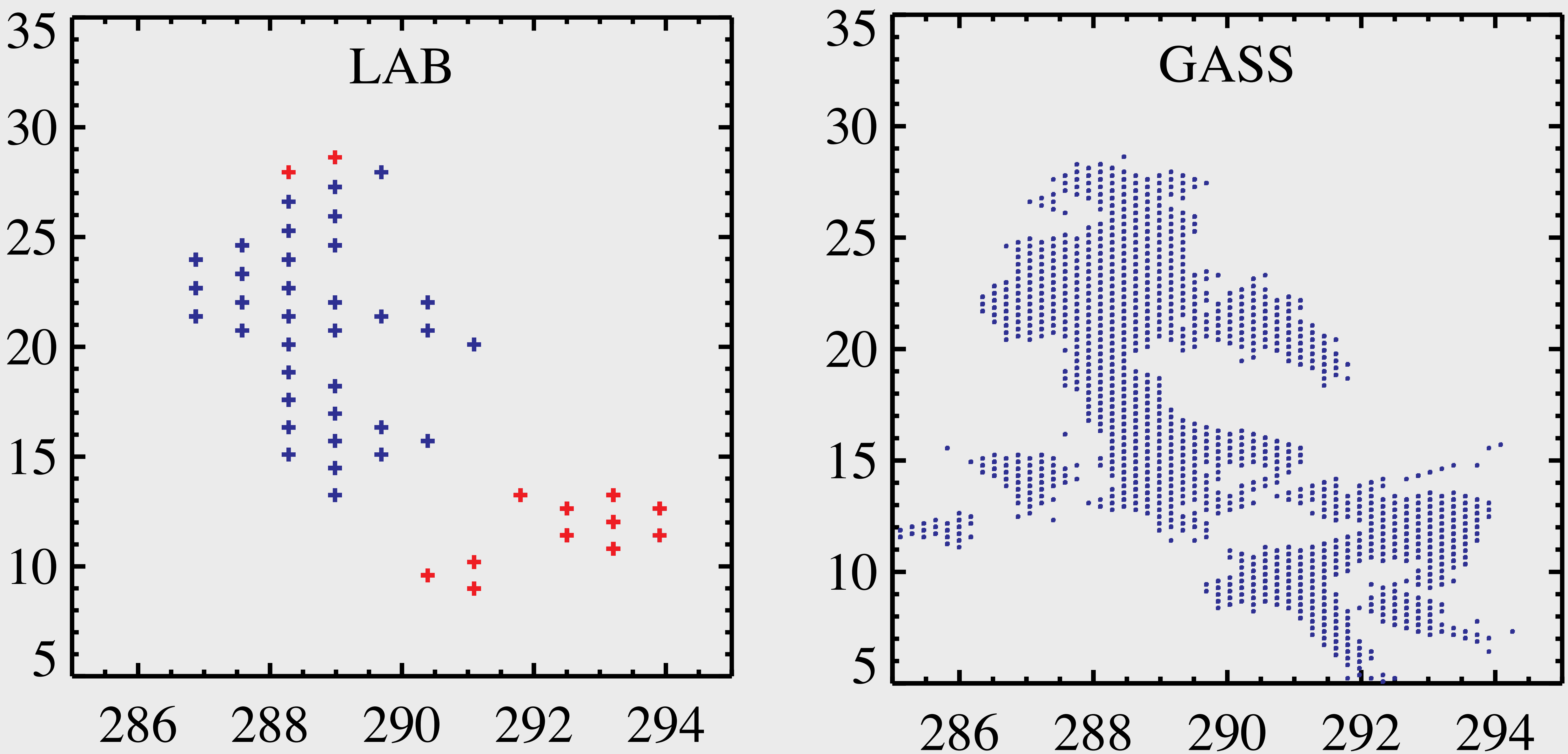
Lowest Level



In LAB this is 4 clouds in GASS 10.

Higher resolution changes the results.

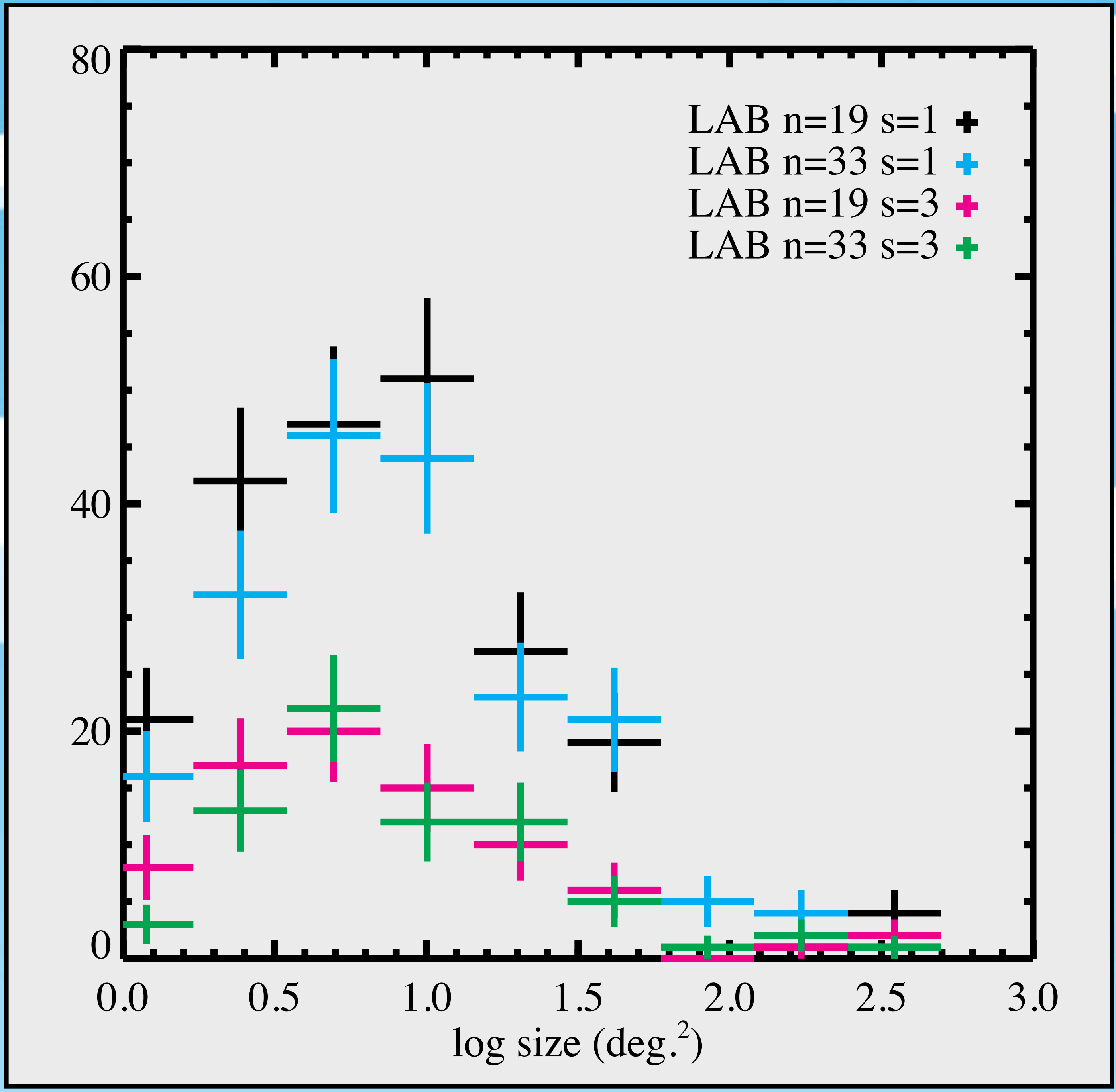
Highest Level



However with a hierarchical structure finder changes in the higher level structure are minimized.

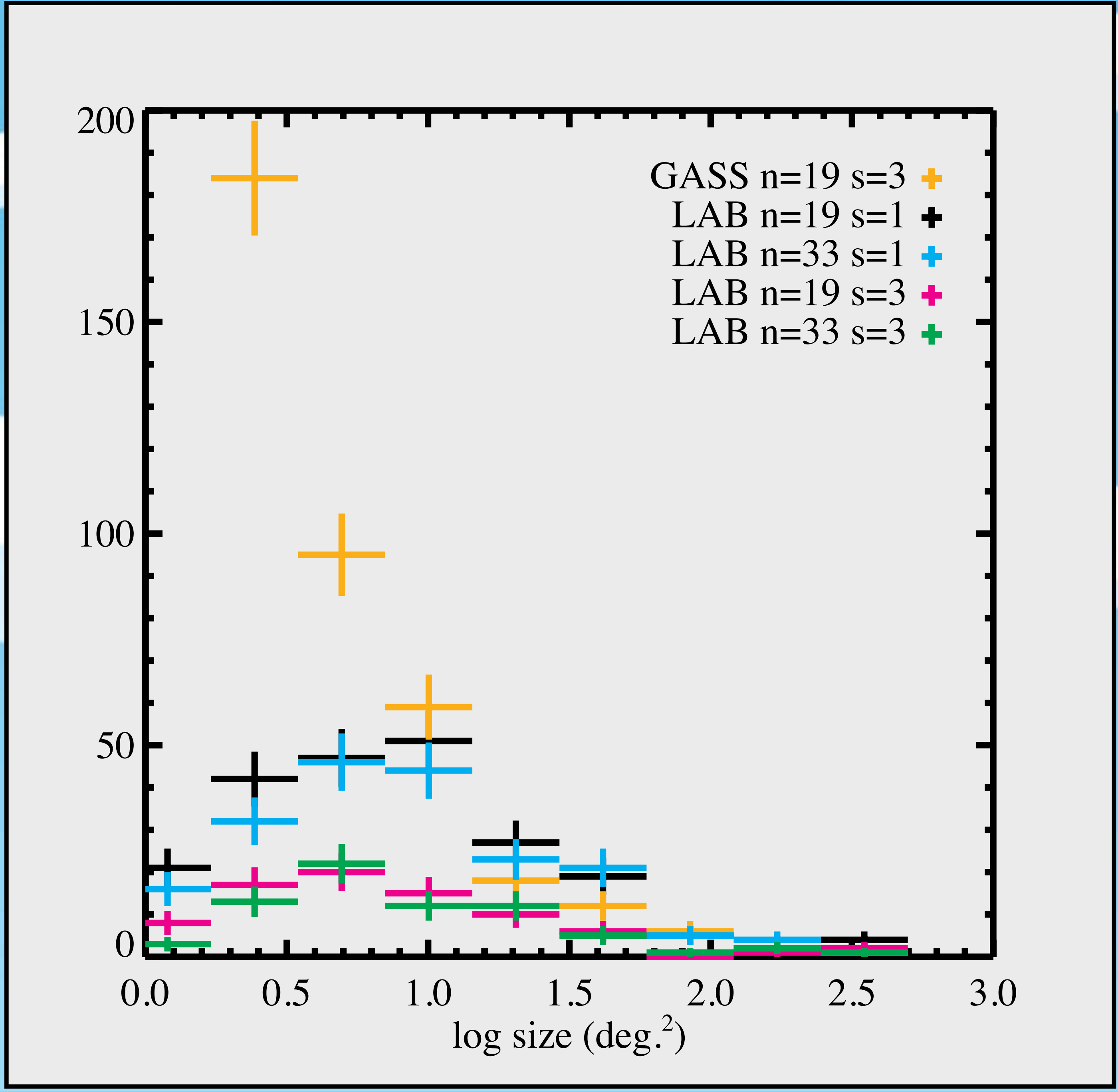
EnLink has only 2 parameters, the number of cells you smooth over, n, and how significant a group needs to be to count, s.

Results seem to be insensitive to n, but depend on s. There is a clear sign of incompleteness below ~10 sq. degrees.

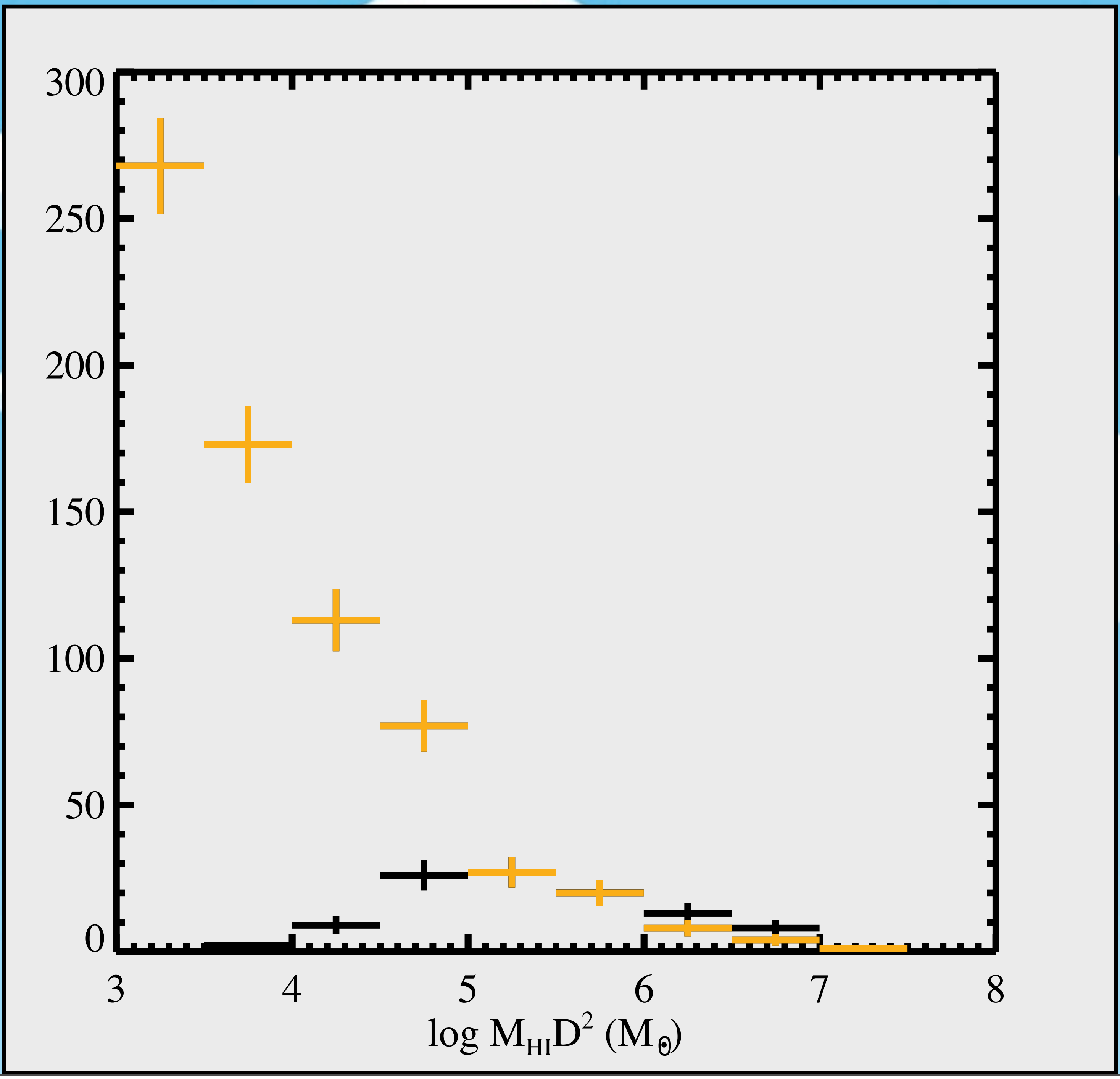


Adding the GASS data we see very good agreement with the s=1 LAB clouds for sizes above 10 sq degrees.

GASS has many more small clouds where LAB is incomplete. It is clear that constraints from high velocity clouds are only good to a limiting size.



Of course we do not know distances to high velocity clouds, so they can only be used to constrain halo clouds with a model of the mass and radial distribution of the "clouds".



If the clouds are all at the same distance this is there mass distribution.

If at

1 kpc this is 1.3e8Msun

10kpc this is 1.3e10Msun

50kpc this is 3.2e11Msun

Maller & Bullock suggest 2e11 Msun

Conclusions

- We are able to identify structures around the Galaxy in a way that is robust above ~10 sq. degrees.
- This can be used to constrain the mass of halo clouds around the Milky Way and thus galaxy formation models.